Jets from Sub-Parsec to Kiloparsec Scales: A Physical Connection

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ABSTRACT

The *Chandra* discovery of bright X-ray emission from kpc-scale jets allows insight into the physical parameters of the jet flow at large scale. At the opposite extreme, extensive studies of the inner relativistic jets in Blazars with multiwavelength observations, yield comparable information on sub-parsec scales. In the framework of simple radiation models for the emission regions we compare the physical parameters of jets on these two very different scales in the only two well studied Blazars for which large-scale emission has been resolved by *Chandra* . Notably, we find that the relativistic Doppler factors and powers derived independently at the two scales are consistent, suggesting that the jet does not suffer severe deceleration or dissipation. Moreover the internal equipartition pressures in the inner jet and in the external X-ray bright knots scale inversely with the jet cross section as expected in the simple picture of a freely expanding jet in equipartition.

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1. Introduction

The study of extragalactic jets has been renewed recently by the *Chandra* discovery of numerous jets bright in X-rays on kiloparsec and larger scales (Chartas et al. 2000; Worrall et al. 2001; Siemiginowska et al. 2002; Sambruna et al. 2002). In powerful sources, the X-rays from the extended jet constitute a spectral component separate from the radio-to-optical synchrotron emission. The latter can be interpreted as inverse-Compton (IC) scattered cosmic microwave background (CMB) photons, produced by the same population of relativistic electrons which emit the radio to otical synchrotron radiation (Tavecchio et al. 2000a, Celotti et al. 2001; but see Dermer & Atoyan 2002 and Stawarz & Ostrowski 2002 for alternatives). The model requires that these X-ray bright jets are still relativistic, with bulk Lorentz factors $5-10$, at distances $\gtrsim 100$ kpc. Fitting the two spectral components with this kind of model and the additional hypothesis of equipartition constrains the main physical quantities of the jet, including the Doppler factor, the magnetic field, the density, energy distribution and, notably, the minimum Lorentz factor of the emitting relativistic electrons, $\gamma_{\rm min}$.

On much smaller scales, the innermost regions of jets in the brightest blazars have been extensively studied through multifrequency observations (e.g., Maraschi & Tavecchio 2001). The double-humped radio-to-γ-ray spectral energy distributions of these sources can be modeled as synchrotron plus inverse-Compton emission, yielding robust estimates of the basic physical quantities of the emission region close to the central black hole (e.g., Ghisellini et al. 1998, Kubo et al. 1998, Sikora & Madejski 2000, Sikora 2001). From this type of models the jet power close to the central black hole was estimated (Ghisellini & Celotti 2002, Maraschi & Tavecchio 2003 (hereafter MT03)).

Comparing the physical state of the plasma *in the same jet* on subparsec and kiloparsec scales can offer an important new window on the propagation of jets, as they expand through the broad-line region, the host galaxy, and into the intergalactic medium (e.g., Begelman, Blandford & Rees 1984, Bicknell 1994). As a first step in this direction, we discuss here such a comparison for the only two blazars, 1510-089 ($z = 0.361$) and 1641+399 ($z = 0.591$), for which data are available for both the inner and extended regions of the jet: the blazar cores are well studied observationally and were modelled by Tavecchio et al. (2000b), (2002); X-ray and optical emission from the large scale jets of both blazars was measured in the recent survey with *Chandra* and HST of bright radio jets (Sambruna et al. 2002, Sambruna et al. 2004 (S04)). The two sources were included in the survey because they satisfied the selection criteria of having radio jets of appropriate brightness and size, irrespective of their previously known blazar properties. The plan of the paper is as follows: in Section 2 we summarise the modeling on both scales, in Section 3 we compare the physical parameters

derived independently on the two scales; results are discussed in Section 4. Throughout the paper we assume $H_0 = 70$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$.

2. Modeling Jets on Small and Large Scales

2.1. The Inner Jet Model

The spectral energy distributions (SEDs) of the unresolved blazar cores were modelled as synchrotron plus inverse-Compton emission, allowing for both synchrotron and external photons as seeds for the inverse-Compton process. The energy spectrum of the relativistic electrons is assumed to be a broken power law with indices $n_1 < 3$ and $n_2 > 3$. A complete discussion of this model is given by Maraschi & Tavecchio (2003, hereafter MT03) and references therein. In the homogeneous case the model uniquely determines the main physical quantities (magnetic field, electron density and energy, size, Doppler factor) if the spectral shapes around the peaks of the two spectral components are observationally determined and an upper limit to the size of the emitting region is derived from time variability. The absence of a spectral break between soft and hard X-rays indicates $\gamma_{\rm min} \sim 1$ (e.g., Tavecchio et al. 2000b). The model parameters derived in MT03 for the two sources are reported in Table 1. Although not assumed in the modelling, we find a posteriori that the emitting regions are close to equipartition.

While δ is a direct outcome of the radiative model, the bulk Lorentz factor of the flow, Γ, depends on the viewing angle, θ. For the most probable viewing angle, $\theta = 1/\delta$, which is the maximum angle allowed by the given Doppler factor, $\Gamma = \delta$. In addition we report in Table 1 the value of Γ corresponding to a smaller (less probable) viewing angle $\theta = 1/2\delta$.

2.2. The Outer Jet Model

The large scale X-ray/optical radio data for the two sources are presented and discussed in S04. Both jets exhibit a knotty X-ray morphology. For our analysis we used radio, optical, and X-ray fluxes for the first knot well separated from the nucleus in the *Chandra* image: knot B and A for PKS 1510-089 and 1641+399 respectively, at projected distances of 2.9 and 2.7 arcsec (11.8 and 13.5 kpc) from the cores. The X-ray knots are unresolved by *Chandra* : their angular radii were fixed at $1''$, which represents an upper limit to the actual dimension. Radio and optical fluxes were extracted over the same area (see S04). The associated radio knots however appear to be resolved in high resolution maps at the $0.5''$ level (Cheung et al., in prep) thus the adopted radius should not be far from the real one. The present analysis

refers to a homogeneous approximation. The possible existence of strong inhomogeneities, advanced in Tavecchio, Ghisellini & Celotti (2003), but questioned in Stawarz et al. (2004), would affect the results.

The SEDs of the knots are shown in Fig. 1. The data, even though sparse in wavelength coverage, clearly indicate the presence of two emission components, as in the prototypical case of IC/CMB jets, PKS 0637-052 (Tavecchio et al. 2000a). As in that case we modeled each SED with a synchrotron plus IC/CMB model, assuming for the emitting electrons a single power-law energy distribution $N(\gamma) = K\gamma^{-n}$ between $\gamma_{\rm min}$ and $\gamma_{\rm max}$. The latter assumption differs from that adopted for the blazar cores (broken power law). Due to the very limited spectral coverage the higher energy part of a broken power law would be underconstrained here. The comparison of the large scale and small scale jet is still meaningful since the single power law adopted here closely corresponds to the lower energy branch of the broken power law.

The slope of the radio spectrum of the knots is $\alpha_r = 0.7-0.8$, which implies $n = 2.4-2.6$. In both cases the X-ray slope ($0.81\pm$ 0.62, 0.66 ± 0.86) is consistent with the radio slope within the large errors (S04). If, additionally, equipartition between the magnetic and electron energy densities is assumed, the observed fluxes provide a unique value for the physical parameters K, B, and for the Doppler factor, δ, for a fixed size of the emitting region (Tavecchio et al. 2000a).

In the absence of information on the spectral shape in the optical band the optical flux (in the case of PKS 1510-089 only an upper limit is available) can be attributed either to the synchrotron or to the IC component. Here we have chosen the first alternative for 1641+399 and the second for PKS 1510-089 respectively. In any case the weakness of the optical flux constrains the minimum Lorentz factor of the emitting electrons. Given the steepness of the electron energy distribution the latter quantity determines the total electron energy density. Generally not measurable with classical radio observations (because of self-absorption), $\gamma_{\rm min}$ is important for the derivation of the kinetic power of the jet. In the present two cases, $\gamma_{\rm min}$ must be less than ~ 10 in order to reproduce the observed X-ray flux and slope but larger than a few in order not to overpredict the optical flux. This is similar to the cases of the four jets reported in Sambruna et al. (2002) and other jets in the survey of S04, for which $\gamma_{\rm min}$ falls in the range 5-10.

The spectral models for the multifrequency emission from the two knots computed with the equipartition assumption are shown in Fig. 1. The corresponding model parameters are reported in Table 1.

3. The Connection Between Small and Large Scales

In the following we discuss the inner and outer jet "connection" with regard to the bulk velocity, the transported (kinetic) power and the internal energy density/pressure.

3.1. *Bulk motion*

A comparison of the parameters independently derived for the inner and outer jet (see Table 1) shows that the values of the beaming factors (δ) for the two widely separated regions are similar. As mentioned above a determination of the bulk Lorentz factor Γ requires an assumption about the viewing angle. Starting from the largest possible angle for a given value of δ, $\theta_{\rm max} \sim 1/\delta$ for which $\Gamma = \delta$ the minimum value of Γ is $\delta/2$ for $\theta = 0$. Since $\theta = 0$ is unlikely and unpractical, for instance for deprojecting, we report in Table 1 the range in Γ corresponding to viewing angles between $\theta_{\rm max}$ and $\theta_{\rm max}/2$. Note that the value of Γ for $\theta_{\rm max}/2$ is very close to $\delta/2$, corresponding to $\theta = 0$. We discard the possibility of *much larger* values of Γ which are also in principle allowed for angles smaller than $\theta_{\rm max}$ but appear unreasonable in view of the higher implied kinetic powers (MT03).

That powerful jets remain relativistic at large scales was anticipated long ago on the basis of theoretical expectations (Blandford & Rees 1974) and observational evidence of jet one-sidedness and depolarization asymmetry (Laing 1988; Garrington & Conway 1991). From our analysis (summarized in Table 1) we derive the values of the Doppler beaming factors at subpc and 100 kpc scales finding no significant difference. Although some deceleration cannot be excluded, the results do not suggest or require it. Recent numerical simulations for highly relativistic jets are in fact consistent with these conclusions (Scheck et al. 2002).

3.2. *Kinetic power*

An important global quantity that can connect the jet at different scales is the transported power. Assuming that the central engine is stationary when averaged over an appropriately long time scale ($10^5 - 10^6 y$), the transported power should remain constant or decrease along the jet. To fix ideas one could refer to the "internal shock" model applicable both to GRBs and to relativistic jets in radiosources (Spada et al. 2001). The "instantaneous" power emitted by the central engine fluctuates but along the propagation path the fluctuations merge and are progressively smoothed into an almost continuous flow.

For both the inner, unresolved region and the (still relativistic) resolved jet, the trans-

ported power can be computed using the expression

$$P_{\rm j} = \pi R^2 \Gamma^2 (U'_B + U'_e + U'_p) c \tag{1}$$

(Celotti & Fabian 1993), where R is the radius of a cross section of the jet, U'_e, U'_p, and U'_B are the rest frame energy densities of relativistic electrons, protons, and magnetic field, respectively. U'_e can be expressed as [2] $U'_e = n_e < \gamma > m_e c^2$, where n_e is the total electron density and $< \gamma >$ is the average Lorentz factor.

In general there is little direct information about U'_p, the "matter content" of jets. For powerful blazars an indirect argument leads to assume a significant proton content. In fact the "intrinsic" radiative luminosity from the core exceeds the power computed assuming an $e^{\pm}$ plasma, which would lead to substantial deceleration of the jet close to the nucleus (Ghisellini & Celotti 2002, Maraschi & Tavecchio 2003). If instead the electrons are neutralized by protons exerting a negligible pressure, the computed power (dominated by the cold proton component), yields for the inner jet a radiative efficiency of $\sim 10\%$. Thus in the following we adopt the latter assumption.

The derived powers are reported in Tab 1. The range associated with the uncertainty on the observing angle is of about a factor 4. We also tried to assess the reliability of our estimates by checking the sensitivity of the derived parameters on the assumed radius. We verified that a radius smaller by a factor 2 than assumed affects the derived power by a factor of 2 (An approximate analytic treatment gives $P = f^{-2\alpha/(3+\alpha)}$ where f (> 1) is the reduction factor of the size).

The results above are valid for equipartition models. In order to assess the effect of relaxing the equipartition assumption for the outer jet we computed emission model parameters *without assuming equipartition.* Since we have to substitute the equipartition hypothesis with some other condition we choose to fix Γ and compute models for various values of Γ around the equipartition values. δ was derived from Γ with a fixed viewing angle (assumed to be equal to the value derived for the blazar region) within the range reported in Table 1. This was done using analytic approximate formulae for the fluxes rather than performing direct spectral fits to the SEDs.

In Fig.2. we compare the powers resulting from different assumptions. The continuous line represents the power computed applying the the IC/CMB model for different values of Γ, without assuming equipartition (each point along this curve implies a different model which reproduces the observed fluxes). The power increases rapidly at low Γ because of the

[2]This is the approximated version (valid for $\gamma_{\rm min} >> 1$) of the general $U'_e = m_e c^2 \int_{\gamma_{\rm min}}^{\gamma_{\rm max}} N(\gamma)(\gamma - 1) d\gamma$.

larger rest-frame energy densities required by the weaker beaming. For both sources it has a broad minimum in the range of Γs allowed in Table 1.

The equipartition condition (determined only by the synchrotron radio flux) is shown by the dashed line (calculated assuming a fixed value $\gamma_{\rm min} = 10$). The intersection of the continuous and dashed line marks the "equipartition" solution which corresponds (approximately) to the parameters of Table 1 and to the spectral models shown in Fig 1.

For comparison the dotted line shows the power required if X-rays were emitted via the synchrotron self-Compton process (for which the only seed photons are the synchrotron ones). For that model, as noted by Schwartz et al. (2000) for PKS 0637-052, the required power would be extremely large and equipartition far from satisfied.

It is noteworthy that the kinetic power of the outer jet, for an IC/CMB model near equipartition, is close to the power estimated *independently* for the inner jet from the blazar SED (shown Fig. 2 by the thick horizontal dashed line; see also Table 1).

3.3. *Energy densities and pressure*

The internal jet pressure (given by $p = U'_B/3 + U'_e/3)$ in the inner, unresolved jet region can be compared with that estimated in the outer knots. Remarkably the ratio of the inner and outer pressures $(20 - 6 \times 10^{10})$ scales approximately with an inverse square law with respect to the (rest-frame) size of the emission region R $(5 - 4 \times 10^5)$.

Assuming the inner region lies at $r \sim 0.1\,{\rm pc} \sim 3 \times 10^{17}$ cm (Ghisellini & Madau 1996), and computing the distance of the external knots from the angular distance, deprojected with the two values of the viewing angle, we find that the scale factors for R and r are similar within 1 order of magnitude. Thus we can make the hypothesis that the jet is almost conical over 6 orders of magnitude in scale.

Moreover the inner and outer models independently indicate near equipartition. Thus our results are consistent with the very simple picture of a free jet in equipartition as described by Blandford & Königl (1979) where the magnetic field should decay with the cross-sectional area of the jet, A, as $B \propto A^{-1/2}$, and the pressure as $p \propto A^{-1}$.

The fact that the jet is free is consistent with (and supports) the results on the conservation of jet power. The interaction with the external medium should be weak so that only a small fraction of the power can be dissipated through shocks. As a result the jet does not decelerate substantially (at most a factor 2 in Γ). An interesting point about the jet pressure at large scale is that its value is of the same order as the pressure of the gas inferred in the

hot haloes at comparable distances in FRI and FRII host galaxies for which profiles has been measured (e.g., Hardcastle & Worrall 2000, Worrall & Birkinshaw 2000) and in the cluster gas around some intermediate-redshift radio-loud quasars (e.g., Hardcastle & Worrall 1999, Crawford & Fabian 2003). This condition could be associated with the end of the phase of free expansion. $p_{\rm ext} \sim 10^{-11} - 10^{-12}$ erg/cm^3.

4. Conclusions

We have presented a case study of two blazars for which high-quality radio, optical, and X-ray observations of both the small-scale and the large-scale jet are available. The physical parameters in the blazar core region and in the outer knots are reasonably well — and independently — determined.

A comparison between the physical quantities at the two scales indicates that:

1) The jet appears to maintain an almost constant relativistic velocity from subparsec scales to distances of hundreds of kiloparsecs. A deceleration of a factor 2 is allowed but not indicated by the derived parameters.

2) The transported power inferred for the outer jet is remarkably similar to that estimated close to the nucleus.

3) The pressure at the two scales is consistent with a simple scaling relation with the jet cross-section, $p \propto A^{-1}$ and the jet geometry between the two scales is approximately conical.

Admittedly the results are model dependent and the quantitative validity of the derived parameters holds within factors of a few, except for the beaming factor δ which is better determined due to the strong dependence of all quantities on it. Nevertheless it is noteworthy that all the results are consistent with the simple scenario of a freely expanding jet in equipartition.

While other possibilities, such as magnetic confinement (e.g. Begelman, Blandford & Rees 1984), can not be excluded. the conditions for a free expansion are certainly satisfied if we compare the derived pressures in the jet with that of an external medium. The bright external knots could ultimately derive from processes associated with the end of the validity of the conditions of free expansion.

The analysis presented here offers new elements relevant for the understanding of the global behaviour of jets. Clearly more observations are needed. While angular resolution, important to investigate the issue of sizes and locations of knots in jets, is not likely to

improve significantly in the near future, deeper observations and the study of a larger number of sources will certainly provide a wider context for investigating the issues addressed here.

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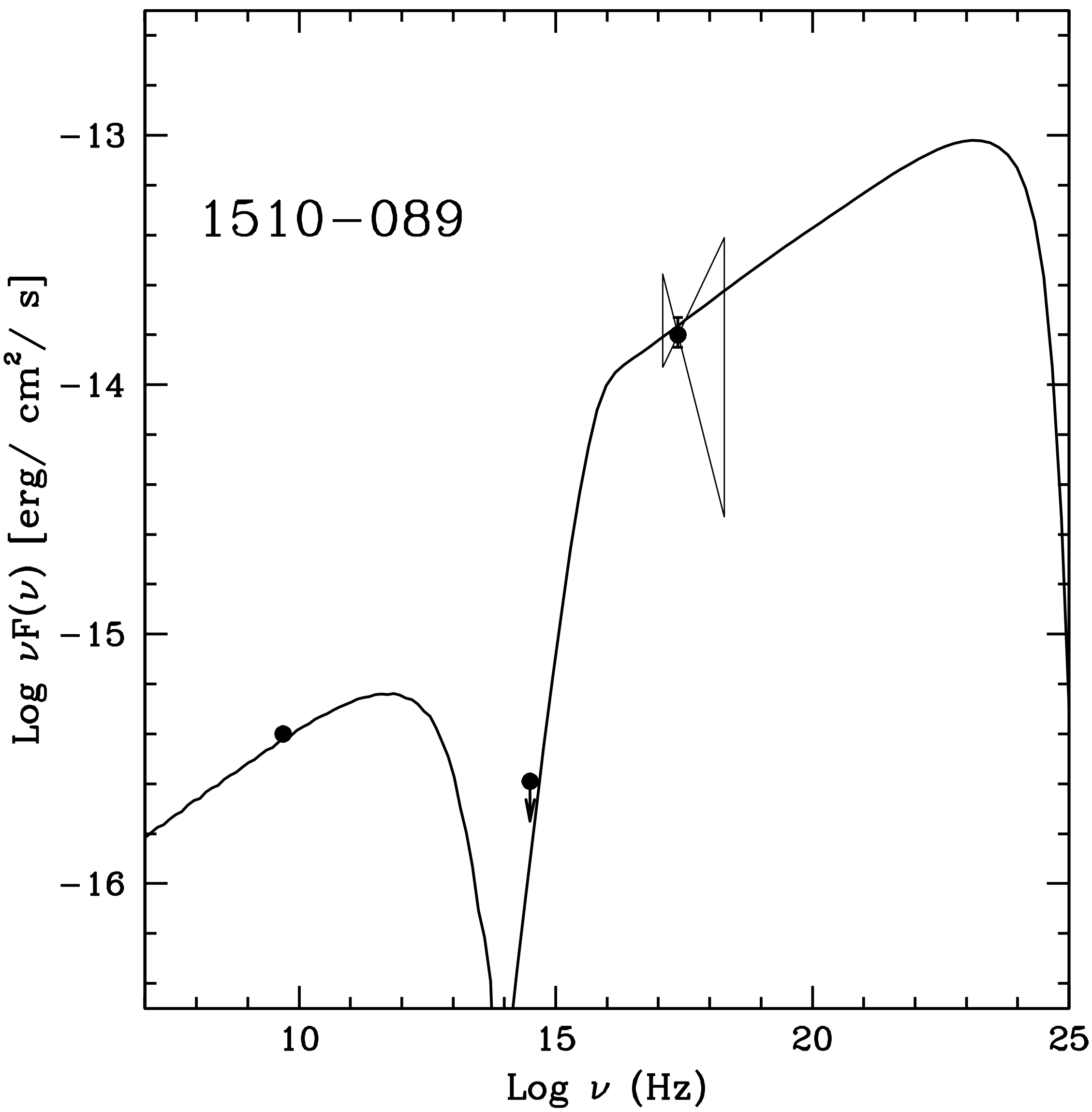
Figure Captions

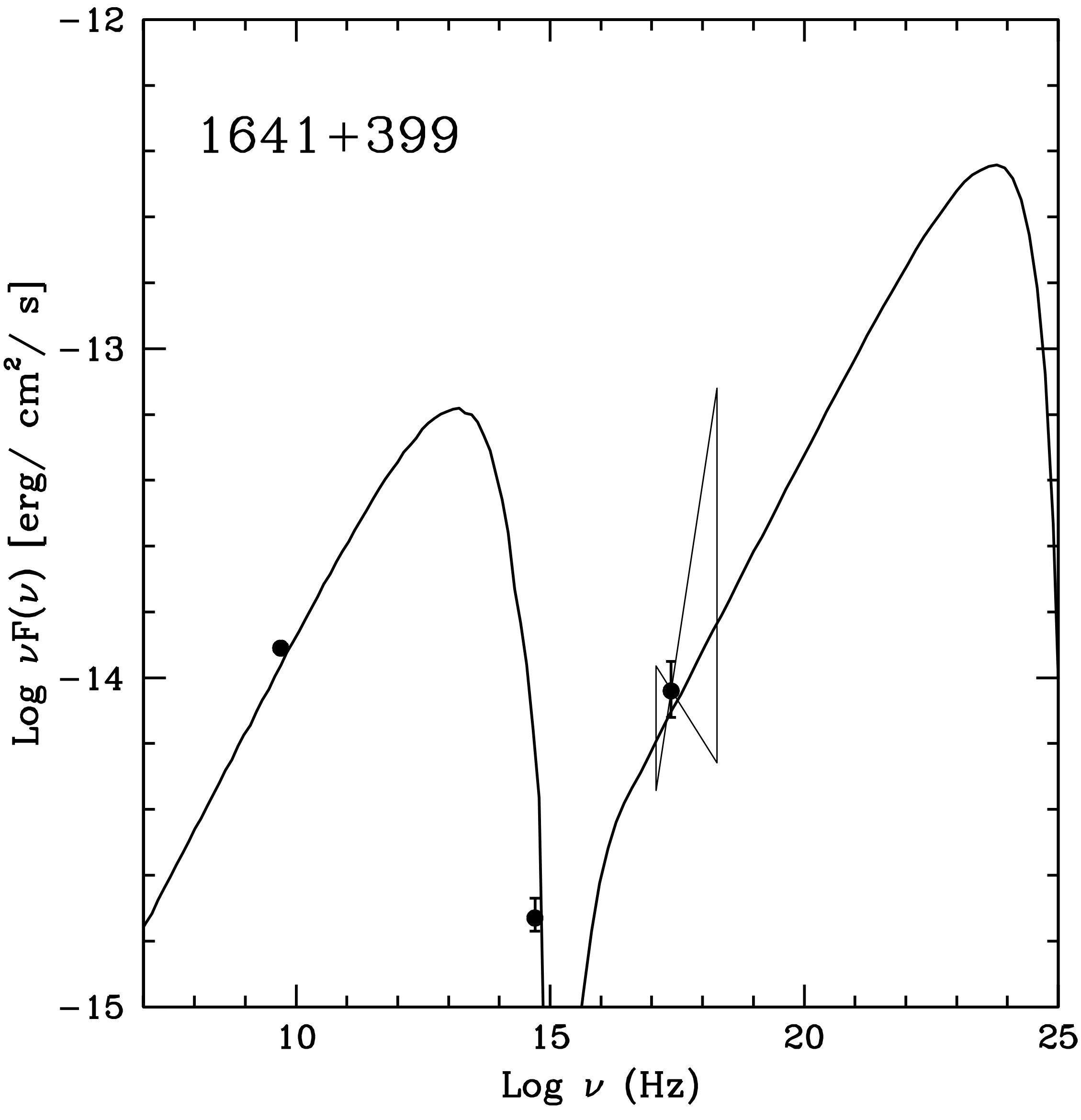
Fig. 1.— Spectral Energy Distributions for the knots of the blazars 1510-089 and 1641+399 analyzed in this work. For 1510-089, only an optical upper limit could be obtained. The solid line is the synchrotron-IC/CMB model used to reproduce the data (see text for details).

Fig. 2.— Jet power inferred on the kiloparsec scale and in the core for 1510-089 and 1641+399. The intersection of the large-scale power estimated using equipartition (short-dashed line) and that estimated with the IC/CMB model (solid line) is very close to the core power (long dashed horizontal line). The power required by a synchrotron self-Compton model (dotted) is much larger, well above the usual power estimates in these sources.

	Parameters of the radiative model						Inferred quantities		
	$\gamma_{\rm min}$	n	U'_B erg/cm^3	U'_e erg/cm^3	R cm	δ	Γ	$P_{\rm j}$ 10^{47}erg/s	r cm
1510-089									
inner	1	1.7	8.9×10^{-2}	9.5×10^{-2}	3×10^{16}	19	19-9.5	5-1.25	3×10^{17}
outer	10	2.7	4.1×10^{-13}	4.15×10^{-13}	1.3×10^{22}	16	16-8.6	4.4-1.3	$0.6\text{-}1.1\times10^{24}$
1641+399									
inner	1	1.5	0.3	0.4	4×10^{16}	9.7	9.7-5	1.2-0.3	3×10^{17}
outer	10	2.4	5.3×10^{-12}	6.4×10^{-12}	1.5×10^{22}	8	8-4.3	4.2-1.1	$3.2\text{-}6.5\times10^{23}$

Table 1: Physical parameters estimated for the inner blazar jet (first line) and for the knot at large distance (outer jet, in the equipartition case, second line) for the two sources. For the core blazar region we report only the first index of the electron distribution ($n = n_1$). δ is the Doppler factor, R indicates the radius of the (spherical) emitting region, r is the distance of the region from the central black hole. We indicated the allowed ranges of Γ, $P_{\rm j}$ and r (for the outer jet only). See text for details.


1510−089
Log νF(ν) [erg/ cm²/ s]
Log ν (Hz)
−13
−14
−15
−16
10
15
20
25


1641+399
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Log ν (Hz)
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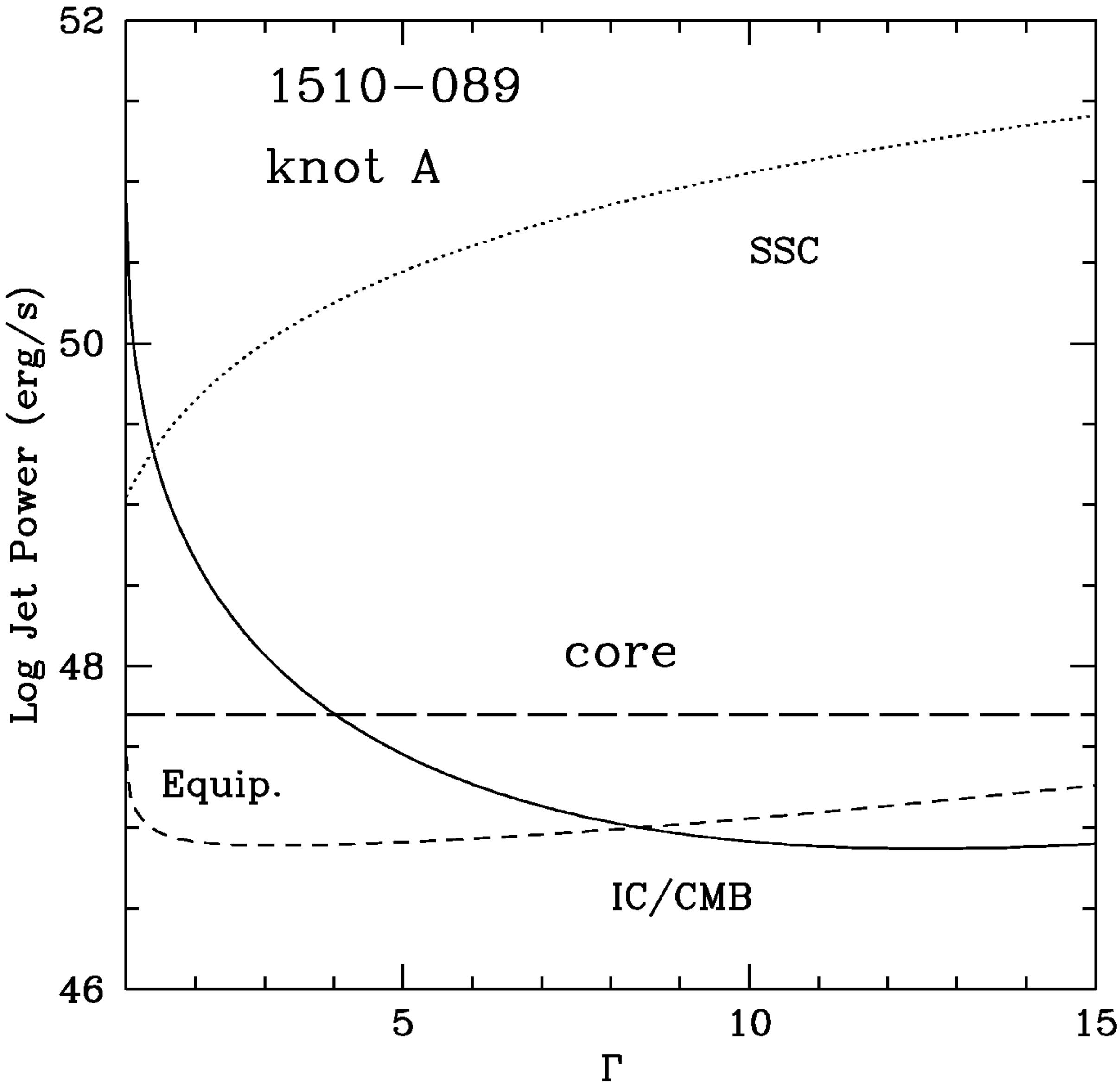
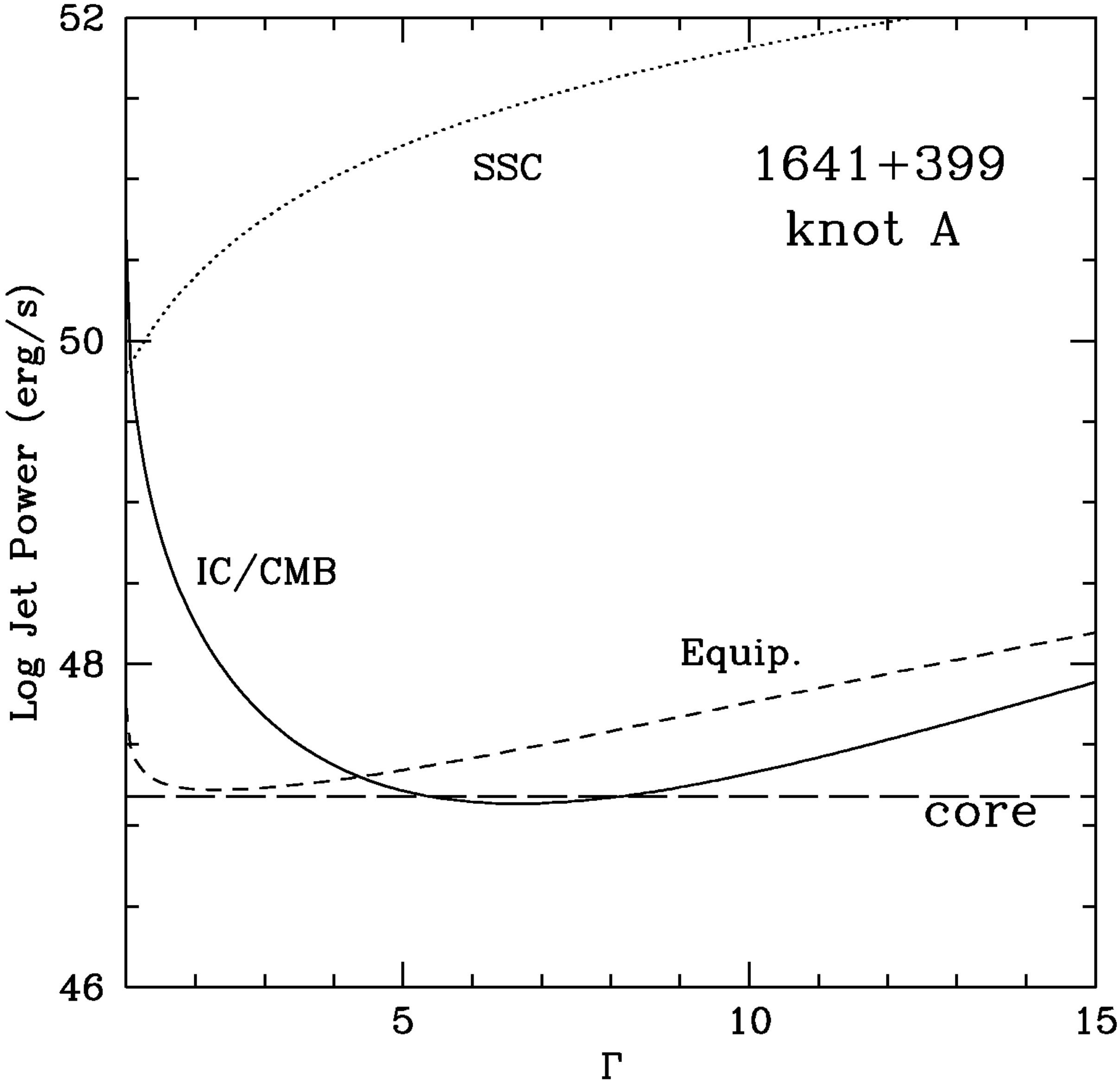


1510−089
knot A
SSC
core
Equip.
IC/CMB
Log Jet Power (erg/s)
Γ
52
50
48
46
5
10
15


52
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Γ
Log Jet Power (erg/s)
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1641+399
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